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Thermal and optical analysis of switchable window glazings

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Glazing materials with variable optical properties (switchable glazings) offer the ultimate in control over the light and energy entering a building. Products of this kind are in their initial stages of development, and guidelines that relate window energy performance to glazing material properties are needed. Though the use of a computer program for calculating window thermal and optical performance parameters, we evaluated (1) the relative performances of three switchable glazings prototypes with differing solar transmittance spectra; (2) the differences between glazings that switch from transmitting to reflecting and those that switch from transmitting to absorbing; and (3) the effects of positioning the switchable glazing in a window. We focused on design conditions for cooling-dominated buildings, since switchable glazings are expected to reduce cooling and lighting loads. We conclude that the differences in thermal performance between absorbing and reflecting switchable glazings can be eliminated through proper placement of the glazing in a window system and through the use of other spectrally selective glazings.

1. Introduction

Heat gains and losses through windows in commercial buildings have a large impact on the overall building's energy use and electric utility peak demand. Previous studies considered the impacts of glazing type, glazing area, shading devices, and lighting controls on energy consumption and demand in an office building for various locations [1–4]. Fig. 1 shows the strong influence that glazing type and lighting controls have on total energy consumption as a function of the window-area-to-exterior-wall-area ratio for an office building in Los Angeles [4]. Continuously dimmable lighting controls can be used to reduce lighting requirements by taking advantage of the available daylight.

Ideally, one would like to customize window properties to balance lighting, heating and cooling loads within each building zone by taking advantage of daylight and, when needed, solar heat gain. To accomplish this, the glazings must affect the quantity, spectral content, and spatial distribution of the incoming solar radiation. Commercially available products that serve this function today are limited to operable shading systems and static selective glazings. Operable shading systems are placed on the interior, exterior, or between the glazing layers of a window, can be

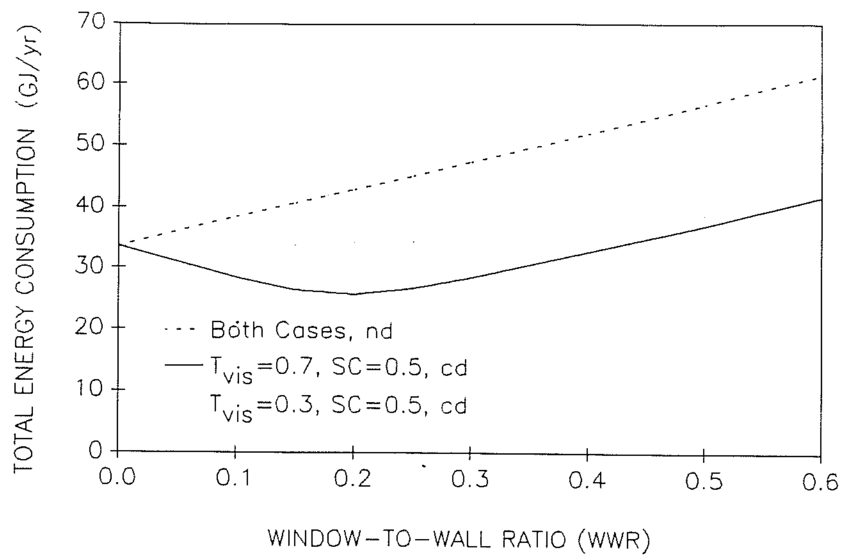

Fig. 1. Total annual energy consumption as a function of the ratio of window area to exterior wall area for the south-facing zone of a Los Angeles office building with a single-zone constant-volume system, a cooling COP of 3.0, a heating efficiency of 0.6, and a lighting power density of 18 W/m^2. The notation is: SC – shading coefficient, T_{vis} – visible transmittance, nd – no lighting controls, cd – lighting controls.

controlled manually or automatically, and can control the quantity and angular distribution of the incoming solar radiation. Unfortunately, operable shading systems that provide this degree of control are expensive and often require a high degree of maintenance. Static selective glazings refer to tinted glazings and selective coatings that are deposited on glass or plastic. These glazings selectively reflect unwanted visible, solar infrared, or infrared radiation incident on the window.

Future prospects for advanced glazings include fine-tuned selective glazings and thin-film technologies which have variable optical properties. An example of a fine-tuned selective coating is one that transmits most of the incident visible light, reflects all of the solar infrared radiation, and has a low infrared emittance. Glazings coated with thin films having variable optical properties are commonly known as switchable glazings, "smart windows", or chromogenic devices. Three types of chromogenic devices being explored today are: (1) electrochromic; (2) thermochromic; and (3) photochromic devices. The optical properties of these devices vary from a high-transmittance bleached state to a low-transmittance colored state depending on the "input" to the device. The optical properties of electrochromic devices change with applied current, those of thermochromic devices change with temperature, and those of photochromic devices change with the amount of incident radiation. Switchable glazings thus offer the potential for the ultimate control of solar radiation entering a space.

Of the switchable glazings mentioned, electrochromic devices hold the greatest potential for commercial building applications. The control of the device's optical properties can be linked directly to building environmental conditions, as opposed to being controlled by climatic conditions alone. This paper gives a brief description

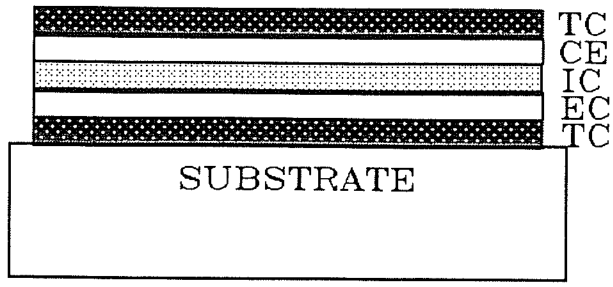

Fig. 2. Schematic of a solid-state electrochromic device: TC – transparent conductor; CE – counter-electrode; IC – ion conductor; and EC – electrochromic.

of electrochromic devices, details the procedure used to evaluate the performance of prototypical electrochromic glazings, and presents performance guidelines based on idealized upper and lower bounds of operation for these glazings.

2. Electrochromic devices

An electrochromic device usually consists of four or five layers (fig. 2), only one of which switches. An ion conductor layer separates the electrochromic layer from the counter-electrode. The two outside layers are transparent electronic conductors, although the counter-electrode and one transparent conductor can be combined into a single layer [5]. A low voltage is applied across the transparent conductors, moving ions from the counter-electrode to the electrochromic layer to trigger a change in transmittance. Reversing the voltage restores the device to its previous optical state.

The success of electrochromic glazing materials depends on the materials' spectral response, visual uniformity, power requirements, reversibility of charge, response time, durability, and the ability to economically fabricate large-area devices. Different classes of materials exhibit electrochromism, and those of potential use in window applications are generally either transition metal oxides or organic materials. Refs. [6–10] discuss the properties and performances of various electrochromic devices and address some of the above issues.

3. Thermal and optical analysis

Materials scientists are striving to optimize the thermal and optical performance of electrochromic glazings for window applications with only cursory guidelines. To improve these guidelines, we evaluated and compared the performance of three prototypical electrochromic glazings whose transmittance spectra bound the possible range of switching over the solar spectrum (0.32–2.5 μm). Each of the prototypes switches from either transmitting to reflecting or transmitting to absorbing over the solar spectrum and has a surface infrared (5–25 μm) emittance equal to that of either uncoated glass ($\epsilon = 0.84$; fig. 3a) or glass coated with a low-emittance film [#1] (low-E, $\epsilon = 0.08$; fig. 3b). While no real material has such sharply defined properties, these 12 ($3 \times 2 \times 2$) cases encompass the operating limits for electrochromic glazings and allow us to assess the importance of the various material characteristics.

The three transmittance spectra are defined as follows:

SOL – transmittance varies over the entire solar spectrum (fig. 4a);

I–R – transmittance varies only over the solar infrared region, and is a constant and a maximum in the visible range (fig. 4b); and

VIS – transmittance varies only over the visible range, and is a constant and a minimum in the solar infrared region (fig. 4c).

As shown in fig. 4, we assumed that the electrochromic layers have a maximum transmittance of 0.8 and a minimum transmittance of 0.1 in the solar spectrum. An actual electrochromic device may operate over this range or a portion of this range. Note that approximately 47% of the energy in the solar spectrum is solar infrared radiation, which serves only as heat gain to a space.

The solar reflectance of each glazing is equal to either one minus the transmittance (reflecting case) or zero (absorbing case). In a cooling-load-dominated building, a reflecting glazing has a less negative energy impact than an absorbing glazing with the same transmittance. There is also a greater risk of breakage due to potentially high thermal stresses in absorbing glazings. However, glazings with high exterior reflectances can create excessive glare and, depending on location, can impose cooling loads on neighboring buildings.

We studied double-pane windows (fig. 5) with a 12.7 mm gapwidth. The non-electrochromic glazing layer in the double-pane windows is either clear glass, green glass, glass with a low-E coating, or glass with a spectrally selective coating (fig. 3). All glazing coatings, including the electrochromic devices, are assumed to face the air gap in the window. Table 1 summarizes the double-pane window configurations studied.

We evaluated the performance of these electrochromic windows at ASHRAE Standard Summer Conditions ($T_{out} = 31.7\,°C$, $T_{in} = 23.9\,°C$, wind speed = 3.3 m/s, and incident solar radiation = 783 W/m^2) in order to focus on cooling-load-dominated buildings. The most relevant window performance indices for such buildings are the shading coefficient (SC) and the visible transmittance (T_{vis}). SC is a measure of the relative amount of solar heat gain through a window (normalized to clear 3 mm glazing), and T_{vis} is a measure of the fraction of incident visible light that a window transmits. The ideal window for a cooling-load-dominated building would have a low SC and a means for modulating the incoming visible light (T_{vis}) to control glare. Lighting controls to reduce electric lighting requirements would be necessary to take advantage of the available daylight [11].

We modified WINDOW 3.1, a steady-state program for calculating the thermal and optical performance indices of windows [12], to compute the SC and T_{vis} for the

[#1] Like uncoated glass, low-E coated glass is transparent to visible radiation and opaque to infrared radiation. However, unlike uncoated glass which absorbs and then emits infrared radiation, low-E coated glass reflects all incident infrared radiation, thus drastically reducing radiative transfer.

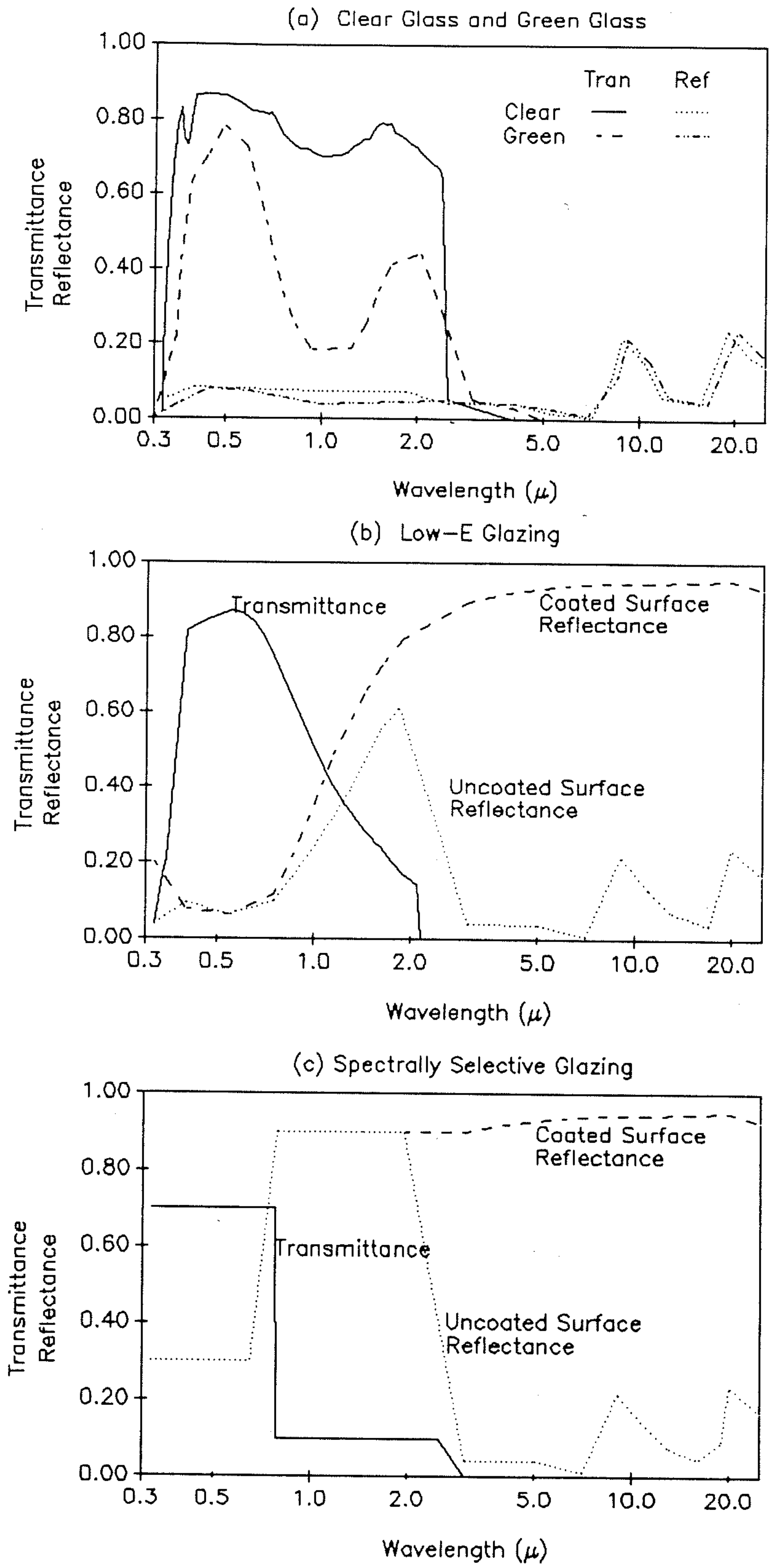

Fig. 3. Transmittance and reflectance spectra of: (a) clear glass and green glass; (b) clear glass with a low-E coating; (c) spectrally selective glazing.

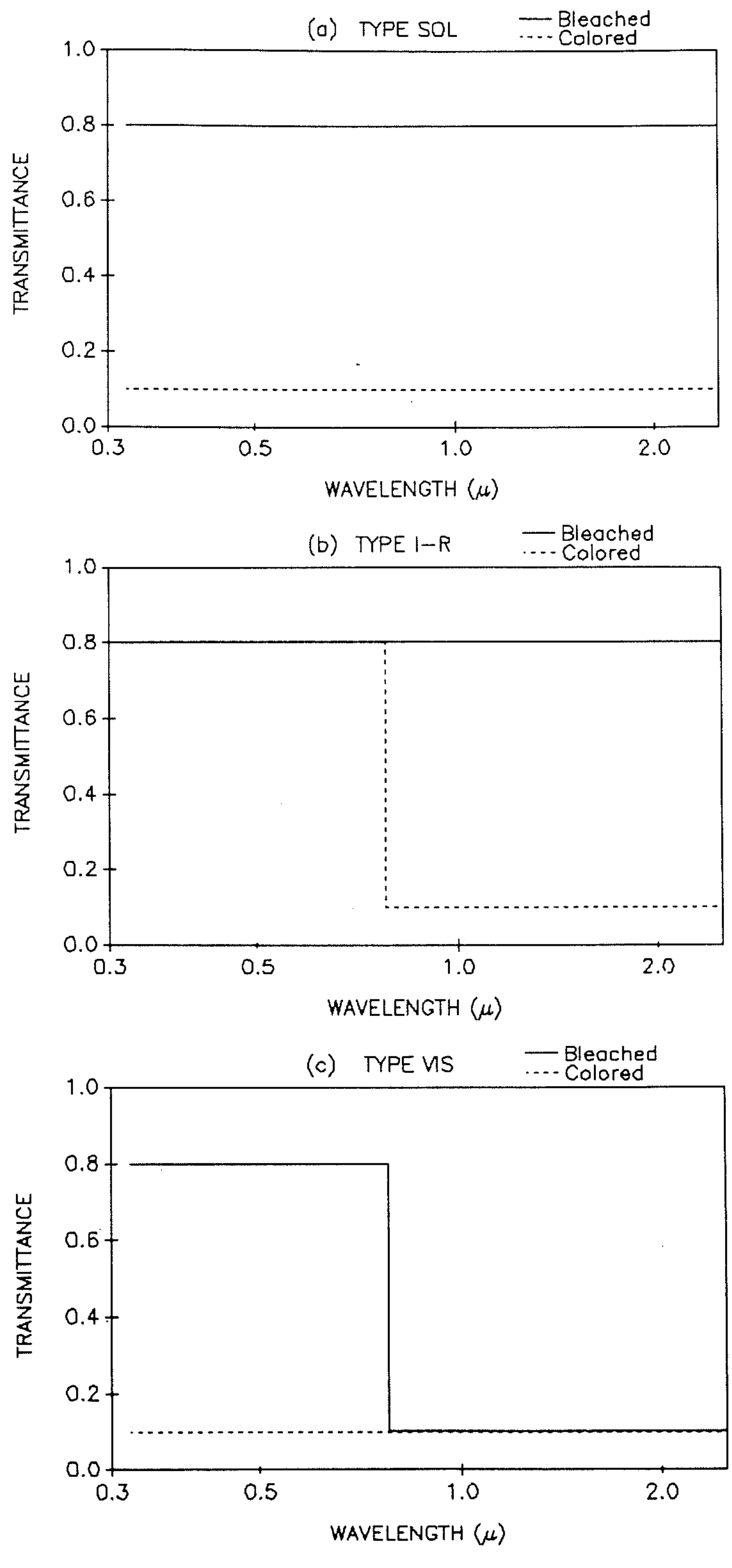

Fig. 4. Solar transmittance spectra of the three electrochromic prototype devices modeled in this study. The properties of the devices switch between the bleached (solid line) and colored (dotted line) states.

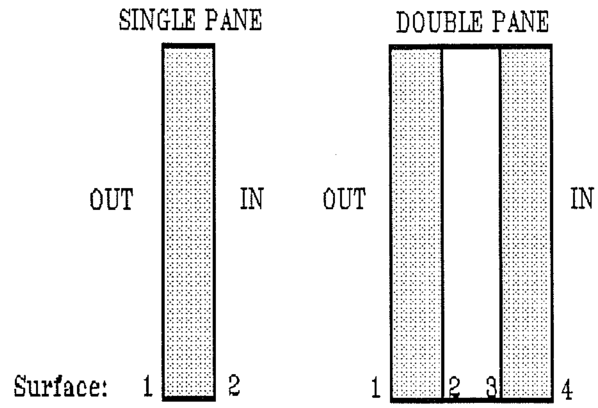

Fig. 5. Schematic of a single-pane and a double-pane window in cross-section.

window systems. This modified version determines the directional-total optical properties for a window system wavelength by wavelength from user-supplied spectral data files. It then calculates the weighted-average properties over the visible, solar, and infrared spectra. The solar properties are weighted by the solar spectral irradiance function of Mecherikunnel and Richmond [13]. The visible properties are also weighted by this function along with the CIE photopic response of the eye [14]. The angle of incidence is assumed to be near-normal for these calculations. The hemispherical infrared properties are weighted by a Planck black-body power spectrum at 300 K.

Table 1
Double-pane window combinations studied in this work

Glazing [a)]	Electrochromic position [b)]	EC [c)]			EE [d)]		
		SOL [e)]	I–R [e)]	VIS [e)]	SOL [e)]	I–R [e)]	VIS [e)]
Clear	Out	X	X	X	X	X	X
Clear	In	X	X	X	X	X	X
Green	Out	X	X	X	X	X	X
Green	In	X	X	X	X	X	X
Selective	Out	X	X	X	X	X	X
Selective	In	X	X	X	X	X	X
Low-E	Out	X	X	X			
Low-E	In	X	X	X			

a) Glazing refers to the non-electrochromic layer.
b) Position of the electrochromic glazing in the double-pane window: out – electrochromic glazing is on the outside layer, no. 2 surface; in – electrochromic glazing is on the inside layer, no. 3 surface (see fig. 5).
c) EC: electrochromic glazing with the thermal infrared properties of clear glass.
d) EE: electrochromic glazing with the thermal infrared properties of low-E glass ($\epsilon = 0.08$). The low-E coating always faces the air gap.
e) Each electrochromic glazing type was studied as switching from transmitting to reflecting and as switching from transmitting to absorbing.

4. Results

We present the results of a representative set of window configurations to illustrate the relative effects and importance of different electrochromic glazings on window design parameters. First, we compare the performances of the three electrochromic types, e.g., how a reflecting type SOL performs with respect to a reflecting type VIS electrochromic for a specific window configuration. Then we compare the reflecting and absorbing cases for each electrochromic type and with respect to the other electrochromic types. Finally, we briefly discuss the influence of electrochromic glazings with the infrared properties of low-E glass.

The analysis focuses on the results for double-pane windows. The optical performances of single-pane windows are similar to those of double-pane windows with the electrochromic glazing placed on the outside and clear glass on the inside (fig. 6). The performances of different single-pane electrochromic windows in relation to each other are simply the performances of the different electrochromic devices compared to each other. However, the relative performances of double-pane windows depend not only on the type of electrochromic glazing used, but also on the properties of the other glazing used and on the positioning of the two glazings in the window.

Notice that a linear relationship exists between SC and T_{vis} for each electrochromic window (figs. 6–9). Recall that type SOL and type VIS electrochromic devices switch over the visible range. The functional difference between the two is that type SOL switches over the solar infrared region, while type VIS maintains a constant minimum transmittance over this range. Therefore, type VIS has a lower SC than

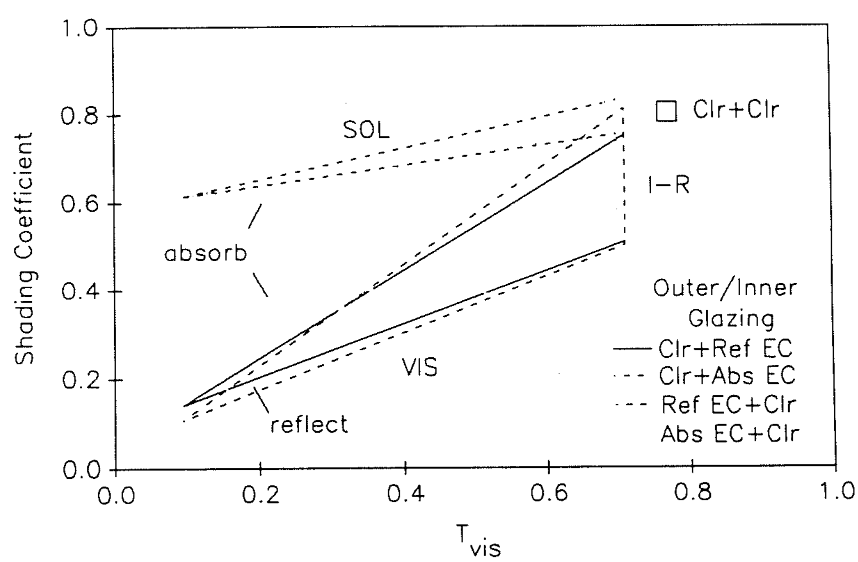

Fig. 6. Performance indices for a double-pane window with clear glass (Clr) and an electrochromic layer with the infrared properties of clear glass (EC). Results are given for reflecting (Ref) electrochromic glazings and absorbing (Abs) electrochromic glazings. For each triangle, the results for a window with: a type SOL electrochromic are represented by the top line; a type I–R are given by the vertical line; and a type VIS are represented by the lower line. The SC and T_{vis} of a window, Clr+Clr, without an electrochromic layer is included for comparison.

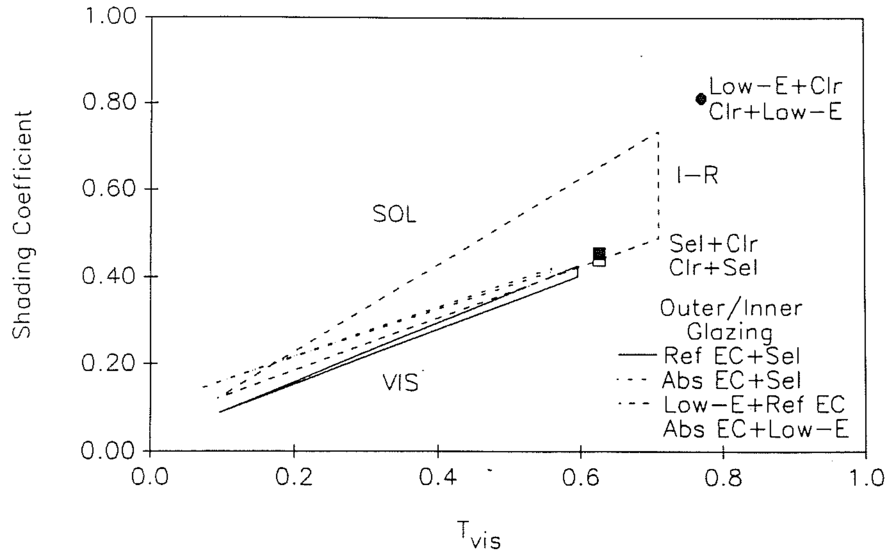

Fig. 7. Performance indices for a double-pane window with either selective glazing (Sel) or low-E glass (Low-E) and an electrochromic layer with the infrared properties of clear glass (EC). Results are given for reflecting (Ref) electrochromic glazings and absorbing (Abs) electrochromic glazings. For each triangle, the results for a window with: a type SOL electrochromic are represented by the top line; a type I–R are given by the vertical line; and a type VIS are represented by the lower line. The SC and T_{vis} of sample windows without an electrochromic layer are included for comparison.

type SOL throughout the T_{vis} range, and the performances of the two electrochromic types converge at a minimum SC and a minimum T_{vis}. A type I–R electrochromic has a fixed T_{vis} and is represented by a vertical line in figures 6, 7, and 9. For a given window, an electrochromic of type I–R has a maximum SC equal to the

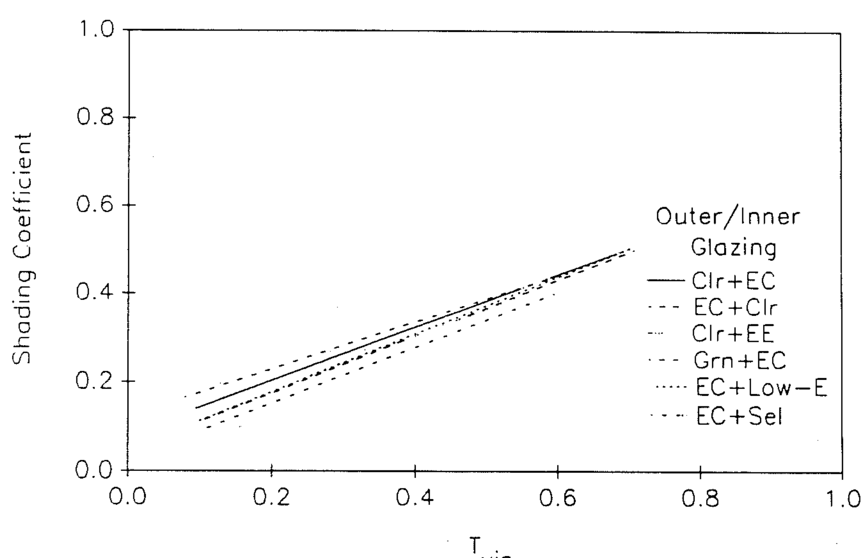

Fig. 8. Performance indices for a double-pane window with either clear glass (Clr), green glass (Grn), low-E glass (Low-E), or selective glazing (Sel) and a reflecting type VIS electrochromic layer (Ref). The electrochromic layer has the infrared properties of clear glass (EC) or low-E glass (EE).

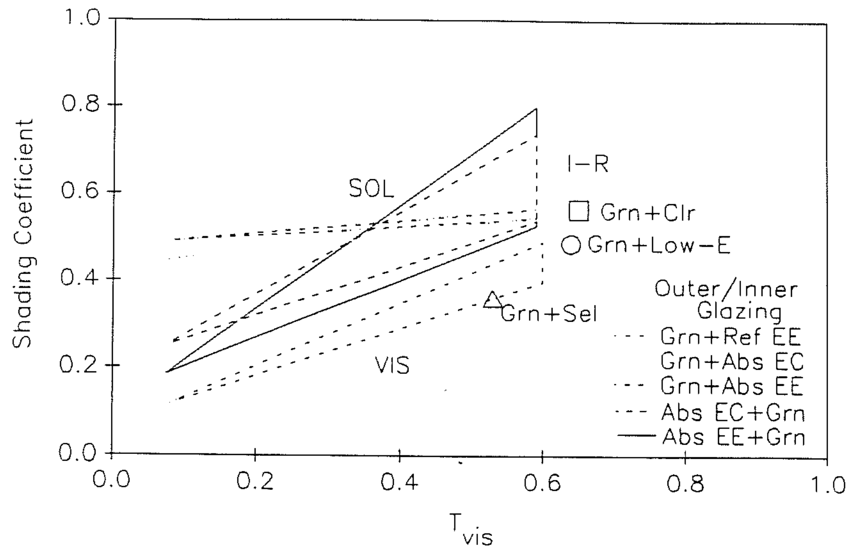

Fig. 9. Performance indices for a double-pane window with green glass (Grn) and an electrochromic layer with the infrared properties of clear glass (EC) or low-E glass (EE). Results are given for reflecting (Ref) electrochromic glazings and absorbing (Abs) electrochromic glazings. The SC and T_{vis} of windows with green glass (Grn) and clear (Clr) or low-E (Low-E) glass are included for comparison.

maximum SC of a type SOL at the maximum T_{vis}, and a minimum SC equal to the maximum SC of a type VIS at the maximum T_{vis}. The triangle formed by the three points of intersection for the three types of electrochromics shows the relative performance of the electrochromic types (figs. 6, 7, 9).

In double-pane windows, the difference in SC between types SOL and VIS depends on the position of the electrochromic glazing and the type of glass used for the second layer. For the window systems studied, smaller differences in SC are generally seen when the electrochromic layer serves as the inside layer (fig. 6). The smallest difference occurs with the selective window configurations (fig. 7). Eliminating the difference between type SOL and type VIS electrochromics by using selective glazings diminishes the need to optimize the spectral behavior of the electrochromic coating itself in the solar infrared region.

An actual electrochromic window will have optical properties between the hypothetical absorbing and reflecting cases. These two cases define the upper and lower bounds, respectively, on SC over the range of T_{vis} for each electrochromic type. Note that the reflecting case always has a lower SC than the absorbing case for the same window. The solar radiation absorbed by an electrochromic glazing will predominantly flow outward when the electrochromic layer is on the outside and inwards when the electrochromic layer is on the inside. Thus, the difference between the reflecting and absorbing cases for each electrochromic type is less when the electrochromic layer is placed on the outside (fig. 6). Note, however, that the type of electrochromic can be as important as whether the device is absorbing or reflecting. For example, in windows with the electrochromic layer placed on the outside, an absorbing type VIS electrochromic has a lower SC than a reflecting type SOL electrochromic over most portions of the T_{vis} range (fig. 6).

Double-pane windows with reflecting electrochromic glazings have the lowest SC. The position of a reflecting electrochromic glazing in a double-pane window that uses clear glass, low-E glass, or selective glass as the other layer makes little difference. Green glass absorbs a considerable amount of solar infrared radiation. Therefore, in a window with a reflecting electrochromic layer of type SOL or I–R and green glass, the green glass should be placed on the outside to achieve a lower SC. For a reflecting type VIS electrochromic glazing, the position of the green glass in the window has a minor impact on the SC because very little solar infrared radiation is transferred by this electrochromic glazing (fig. 8).

Absorbing electrochromic coatings should be placed on the outside glazing to achieve a lower SC if the other glazing is clear, low-E, or selective. An absorbing type VIS electrochromic glazing should also be placed on the outside if the other glazing used is green glass (fig. 9). For an absorbing type SOL electrochromic, if the window operates at a $T_{vis} < 0.35$ most of the time, then the green glass should be placed on the inside. Conversely, if it operates at $T_{vis} > 0.35$, the green glass should be placed on the outside to yield a lower SC (fig. 9). For an absorbing type I–R electrochromic, the positioning of the green glass depends on the amount of desired heat gain to the space (fig. 9).

Absorbing layers are usually placed on the outside to reduce heat gain to the space and to avoid high thermal stresses in the glazing. Some of the cases presented in this paper have absorbing glazings for both layers. Structural analyses would be necessary to determine whether heat strengthening or tempering would be required to alleviate thermal stresses.

The purpose of a low-E coating is to reduce the infrared radiative heat transfer between two glazing surfaces facing each other. The desired switching range for the SC in the window, whether the electrochromic layer is reflecting or absorbing, and the type of glass used for the non-electrochromic layer determine the optimum position for an electrochromic glazing with the infrared properties of a low-E coating. The preferred position of the electrochromic glazing will vary with the particular window design and the building conditioning requirements. The results for windows having green glass and an electrochromic layer with the infrared properties of low-E glass ($\epsilon = 0.08$) or with the infrared properties of clear glass ($\epsilon = 0.84$) are shown in fig. 9.

Figs. 6, 7, and 9 include results for reference windows without electrochromic layers. A single point represents the visible transmittance and shading coefficient of each window and is generally located near the maximum T_{vis} and SC points of the electrochromic windows. Given existing technology, the best window for admitting daylight and controlling solar heat gain would consist of a spectrally selective glazing layer (fig. 3c) and a tinted glazing layer (fig. 9). For example, a double-pane window with green glass on the outside and a spectrally selective layer on the inside would have a T_{vis} of 0.53 and a SC of 0.36 (fig. 9). Lower SC's are attainable through the use of less visibly transparent glass; however, these would diminish daylighting benefits.

5. Conclusions

We studied three electrochromic glazing prototypes in double-pane windows. The solar optical properties of the electrochromic glazings were characterized as switching from either transmitting to reflecting or transmitting to absorbing. The infrared optical properties were taken as those of clear glass ($\epsilon = 0.84$) or low-E glass ($\epsilon = 0.08$). The position of these glazings was varied within different window systems. These window systems had clear, green, low-E, or selective glazing and an electrochromic glazing.

Performance criteria need to be established to help guide the research and development of any new technology. From the results presented above, we identified the following guidelines for improving the thermal and optical performance of switchable glazings:

(1) The smallest differences in SC between the electrochromic windows occur when the electrochromic glazing is placed on the outside. Such placement of the electrochromic layer alleviates some of the concern over whether a device is reflecting or absorbing.

(2) The optical properties of a switchable window can be improved through the integration of a static selective coating into the window system. A static spectrally selective coating that behaves optically like a type VIS electrochromic glazing in its maximum transmittance state can be used with a type SOL electrochromic glazing to make the type SOL perform as a type VIS does. (Static spectrally selective coatings could also be incorporated directly into one of the transparent conductors in the electrochromic stack.)

(3) An absorbing type VIS electrochromic glazing can have a lower SC than a reflecting type SOL electrochromic glazing over certain T_{vis} ranges in a double-pane window with the electrochromic layer on the number 2 surface. This implies that optimization of the transmittance spectra of an absorbing electrochromic layer can yield a lower SC than that of a reflecting electrochromic layer which does not offer the same control over the transmitted radiation. However, such fine-tuning may not be necessary given the findings of conclusion (2).

(4) The position of the glazing within a window with a reflecting electrochromic glazing has little effect on the SC. The exception to this occurs when the non-electrochromic glazing substrate is highly absorbing, in which case the absorbing glazing should be placed on the outside.

(5) If the electrochromic glazing has a low-emissivity surface, the optimum location within the window will vary with the design application. The placement depends on the type of electrochromic, whether the electrochromic is reflecting or absorbing, and the glazing material used for the non-electrochromic layer.

Evaluating and comparing the thermal and optical performances of electrochromic windows necessitates the consideration of total building performance criteria, which are the controlling variables for a building space. These variables determine the heating, cooling, and lighting loads that relate directly to human comfort. To identify a suitable window based on the performance criteria, one must answer many questions, such as: "Is the building dominated by cooling or heating loads, or both?", "When do the building peak cooling, heating, and electric loads occur?", "Are solar gains beneficial during certain times of the year and certain times of the day?", "Will daylighting be used?", "How much visible light is needed, and will glare be a problem?", "Should a single-, double-, or multipane window be installed?", and "Where should the electrochromic device be positioned within the window system?"

The methodology and results detailed in this paper to evaluate the optical and thermal performances of electrochromic glazings will be used with an hour-by-hour building energy simulation program to answer some of the above questions. Past simulation studies [15–18] modeled electrochromic windows as being either in a bleached or a colored state, or as having the SC equal to the T_{vis}. More inclusive analyses of "smart window" technology will provide valuable information to materials scientists developing the coatings, window manufacturers, architects, engineers, and utilities concerned with developing new techniques for load management.

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